

# Mixing Control of a Round Jet by a Local Sound Wave



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**Abstract** Acoustic excitation, moving tabs, a plasma actuator and so on have been presented as methods of active control for a jet. In this study, a round jet is locally excited by a local sound wave radiated from a loudspeaker inputting a sine wave. The excited frequencies were determined with reference to the preferred frequency in the column mode of the jet. The jet was visualized using planar laser Mie scattering. Mean velocity and turbulent intensity on the jet centerline were measured using a hot wire anemometer. As a result, it is found that the acoustic excitation produces anisotropy to the spatial development of the jet, and changes of the flow structure by the frequency of the sound wave. For exciting at the preferred mode, one side of the jet expands and the other side becomes narrow. For exciting at 1/2 frequency of the preferred mode, the asymmetric structure appears in the jet.

**Keywords** Jet • Flow control • Sound wave • Acoustic excitation  
Free shear layer

## 1 Introduction

Jets are widely used in industrial fields, such as mixing, combustion, heat transfer and so on. Many researchers and engineers have done studies for mixing between the jet and the surroundings [1]. Adding periodic disturbance to the jet with a sound wave is considered to be an effective method to control the mixing between the jet and the surroundings [1]. In previous studies, there are many methods adding the sound waves to the whole jet by a loudspeaker [2, 3]. It is necessary to locally give

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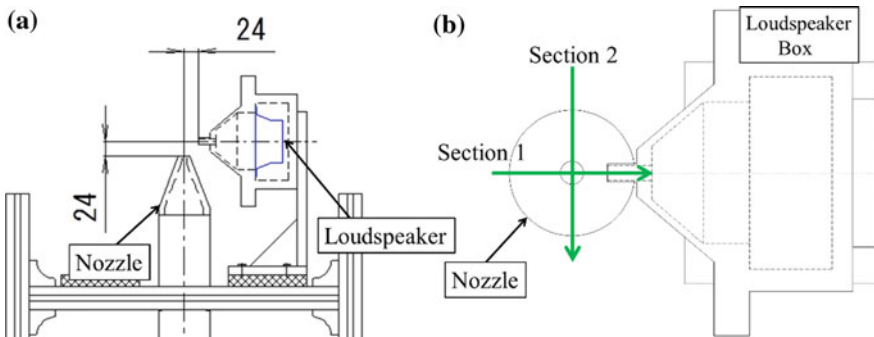
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the jet the disturbance to control the local structure of the jet. The purpose of this study is to experimentally examine the changing of the flow structure and mixing when the shear layer in the initial region of the jet is locally excited with a sound wave. The streamwise sections of the jet are visualized to see the changed flow structure.

## 2 Experimental Apparatus and Method

Figure 1a shows experimental apparatus for manipulating the flow structure of the jet. An air jet is vertically issuing from a round nozzle having an exit diameter of  $D_0 = 8$  mm into the ambient air. A loudspeaker is mounted in a speaker box as shown in Fig. 1a, and a sound wave is added to the jet shear layer through a pipe with an inner diameter of 10 mm. The center of the pipe outlet is radially and axially located at  $3 D_0$  apart from the center of the nozzle exit.

Experimental conditions are shown in Table 1. The Reynolds number of the jet is  $Re = 1,500$  (the issuing velocity on the jet centerline  $U_{c0} = 2.81$  m/s). The preferred frequency of the jet column at the  $Re$  of 1,500 is  $f_v = 180$  Hz. Therefore, excited frequencies  $f_s$  are set to 90 Hz ( $= 0.5 f_v$ ), 180 Hz ( $= f_v$ ), and 360 Hz ( $= 2.0 f_v$ ). The  $St_s$  in the Table 1 is a non-dimensional excited frequency. The excited intensity is indicated with a nondimensional velocity fluctuation  $u'_s/U_{c0}$ , where the  $u'_s$  is the rms value of velocity fluctuation at the outlet of the speaker box and the  $U_{c0}$  is the jet velocity. The value of  $u'_s/U_{c0}$  is set to a constant and 36.2%. The input signal to the loudspeaker is a sine wave. Two streamwise cross sections of the jet are visualized using a planar laser Mie scattering. The two visualized sections are shown in Fig. 1b. The cross Sect. 1 is the incident direction of sound waves and the cross Sect. 2 is vertical to the cross Sect. 1. Mean velocity and velocity fluctuation on the jet centerline are measured using a hot wire anemometer.



**Fig. 1** a A loudspeaker and a round nozzle, b Two visualized sections on the jet centerline

**Table 1** Experimental conditions

Jet gas	Air
$D_0$ [mm]	8
$Re$ [-]	1500
$U_{c0}$ [m/s]	2.81
$f_s$ [Hz]	0, 90, 180, 360
$St_s$ [-]	0, 0.26, 0.51, 1.03
$u'_c/U_{c0}$ [%]	36.2
Input signal for sound wave	Sine wave

### 3 Experimental Results and Discussion

#### 3.1 The Visualized Streamwise Sections of the Jet

Figure 2 shows two cross sections for visualized jets without and with excitation. In Figs. 2, 3, and 4, the  $x$  and  $r$  are axial and radial coordinates respectively, and the origin is the center of the nozzle exit. At the exciting cases in the visualized cross Sect. 1 (the top of Fig. 2), the vortex rings in the jet are inclined due to the advance of the vortex at the incident side of the sound wave. At the excitation frequencies  $f_s = 180$  and 360 Hz in the Sect. 1, the width of the jets slightly becomes narrower than the width in the Sect. 2 (the bottom of Fig. 2), with the spatial development of the jet. When the jet is excited at  $f_s = 90$  Hz, the jet is meandering, as shown in the visualized Sect. 1. After that the vortex ring peels off at a constant height, so that the jet spreads widely. Asymmetric structure appears clearly in the jet. On the other hand, it is found that, in the Sect. 2, the jet is flowing in symmetrical structure. Focusing on the generation frequency of the vortex rings, in the case of the excitation frequencies  $f_s = 180$  and 360 Hz, the generation frequencies of the vortex rings coincide with the preferred frequency. In the case of  $f_s = 90$ , the generation frequency of the vortex rings coincides with the excitation frequency.

#### 3.2 Measured Mean Velocity and Velocity Fluctuation on the Jet Centerline

Figures 3 and 4 show the distributions of non-dimensional mean velocity and velocity fluctuation on the jet centerline. In the case of the unexcited jet, the mean velocity  $U_c/U_{c0}$  almost maintains at constant, and the value of  $U_c/U_{c0}$  is about 0.99 at the position of  $x/D_0 = 10$ . The velocity fluctuation  $u'_c/U_{c0}$  gradually increases, and its value becomes about 6% at  $x/D_0 = 10$ . For the acoustically excited jets except for  $f_s = 360$  Hz, the velocity fluctuations increase and the potential cores become extremely short, as compared with the unexcited jet. Particularly, at  $f_s =$

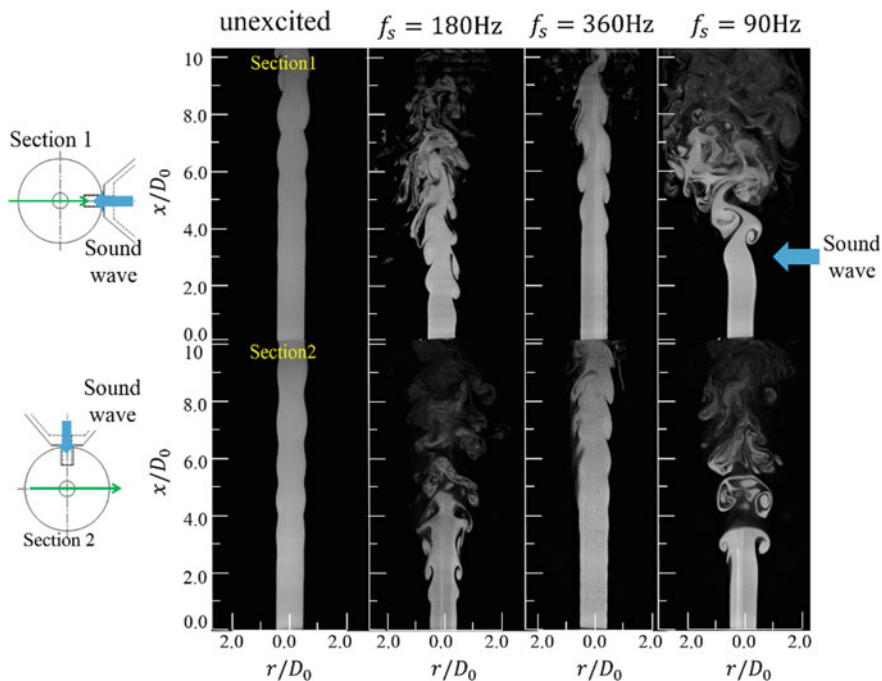
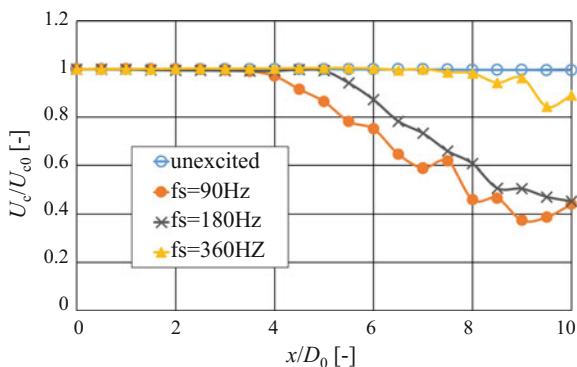


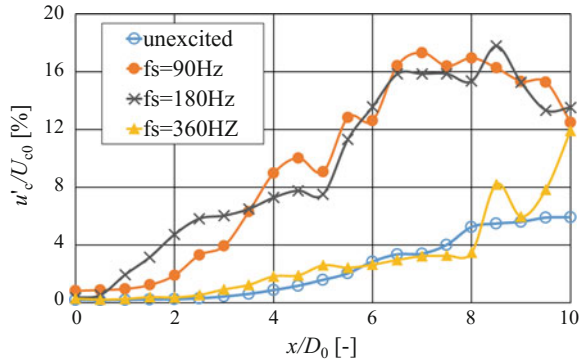
Fig. 2 Visualized air jets

Fig. 3 Axial distributions of mean velocity on the jet centerline (Air,  $Re = 1500$ ,  $f_s = 0, 90, 180, \text{ and } 360 \text{ Hz}$ )



90 Hz, the length of the potential core is shortest and the mean velocity greatly decreases from the position of  $x/D_0 = 4.0$ . At  $f_s = 180$  and  $360 \text{ Hz}$ , the mean velocities decrease from the position of  $x/D_0 = 5.0$  and  $8.0$ , respectively. In the early stage of the jet ( $x/D_0 < 3$ ), the velocity fluctuation is most amplified spatially at the  $f_s = 180 \text{ Hz}$ . For  $x/D_0 > 3$ , the velocity fluctuation is most amplified spatially

**Fig. 4** Axial distributions of velocity fluctuation on the jet centerline (Air,  $Re = 1500$ ,  $f_s = 0, 90, 180,$  and  $360$  Hz)

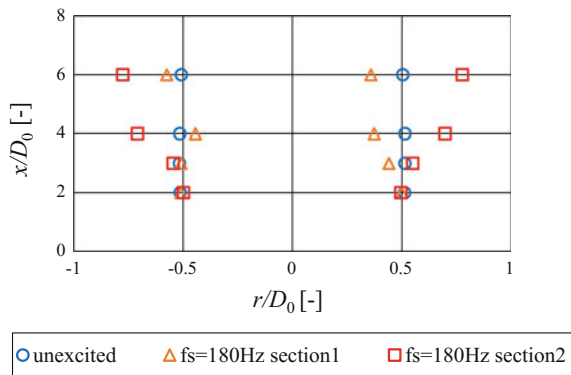


at the  $f_s = 90$  Hz and the mean velocity decays extremely. The velocity fluctuation is not most amplified at the  $f_s = 360$  Hz and is close to the velocity fluctuation in the unexcited jet. The difference of the visualized jets and the distributions of the mean velocity are understood from the variation of the velocity fluctuations.

### 3.3 Half Radius of the Jets

Figure 5 shows the half radii for the unexcited jet and the excited jet at  $f_s = 180$  Hz. For the unexcited jet, in the measured range, the half radii hardly change. For the excited jet, the half radius on the incident side of sound wave in the Sect. 1 decreases at the  $x/D_0 = 3$  of the sound wave incident position. Also, at  $x/D_0 = 4$ , the half radii decrease, and then at  $x/D_0 = 6$ , the jet flow leans to the left. In the cross Sect. 2, the half radii extremely increase to the downstream. It is also found that anisotropy occurred in the spacial development process of the jet from the result of half radii.

**Fig. 5** Half radii of the jets



## 4 Conclusions

The jet shear layer was locally excited by a sound wave. In the excited jets, the vortex rings are inclined due to the advance of the vortices at the incident side of the sound wave. In the jets for excited frequencies of preferred mode and its double, the width of the jet in the section of the incoming sound waves slightly becomes narrower than the width in the perpendicular section, with the spatial development of the jet. When the jet is excited at  $1/2$  frequency of the preferred mode, asymmetric structure appears at the section of the incident sound wave in the jet.

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